CONTROL OF MICROPHONICS AND LORENTZ FORCE DETUNING WITH A FAST MECHANICAL TUNER

Stefan Simrock, DESY, Notkestr. 85, 22603 Hamburg, Germany

Abstract

Microphonics and Lorentz force detuning have a significant impact on the achievable field stability and rf power requirements in superconducting accelerators. The pulsed operation of high gradient cavities results in dynamic Lorentz force detuning approaching or exceeding the bandwidth of the cavity of the order of a few hundred Hz. In energy recovery linacs the highest possible loaded Q is desired to reduce rf power requirements. In this case a typical microphonic noise level of a few Hz is limiting the permitted loaded Q. In both cases detuning control with a fast mechanical tuner using piezoelectric or magnetostrictive actuators appears very attractive. The issues to be addressed are the achievable stroke at low temperatures, mechanical preload to maximize lifetime and associated in situ force measurement, design of the fast tuner fixture including the actuator/sensor configuration, feedforward algorithm for the compensation of repetitive Lorentz force detuning, and feedback algorithm for the control of microphonics.

INTRODUCTION

The control of the resonance frequency of superconducting cavities is highly desirable particularly if frequency excursions induced by microphonics (or Lorentz force detuning in pulsed operation) exceed the bandwidth of the cavity. This is usually the case in accelerators with small beam loading such as heavy ion linacs, low current high energy electron linacs and energy recovery linacs.

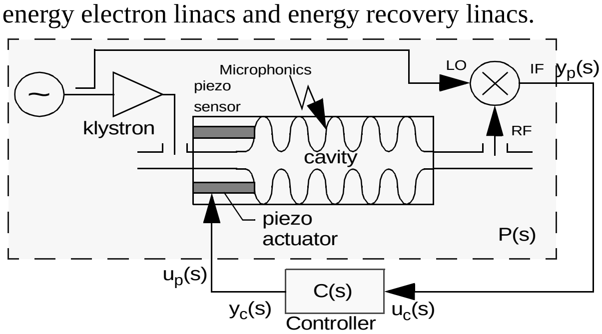

Fig.1: Schematic for feedback control of microphonics

Typical microphonic noise levels as measured in operational superconducting accelerators are of the order of several Hz to several tens of Hz with a frequency spectrum ranging up to a few hundred Hz. The observed spectrum is a result of a convolution of the spectrum of excitation and the coupling to the mechanical resonances of the cavities. Since microphonics are induced by mechanical vibrations a natural solution to the problems appears to be a fast mechanical actuator which is driven in such a way that the detuning caused by microphonics is perfectly compensated. Due to the partially statistical nature of the microphonic noise a negative feedback loop is necessary as shown in Figure 1.

The cavity resonance frequency is detected with a phase detector comparing the wave incident to the cavity (from the directional coupler for forward power) with the transmitted signal (field probe signal). Corrections for beam loading may be necessary and can be accomplished with digital signal processing. The fast mechanical frequency tuner can be realized with a piezoelectric or magnetostrictive actuator which are integrated with the motor driven mechanical tuner. The actuators typically allow for a length change of the cavity of a few micrometers resulting in frequency changes of some tens to some hundreds of Hz. Presently several labs are pursuing the control of microphonics and Lorentz force detuning with a piezoelectric actuator [1-11].

MICROPHONICS CONTROL ISSUES

Fast piezoelectric tuners are installed in several superconducting linacs but are usually used to control slow drifts (< 1 Hz) of the resonance frequency of the cavity. Attempts have been made to increase the bandwidth of the feedback loop to several hundred Hertz.

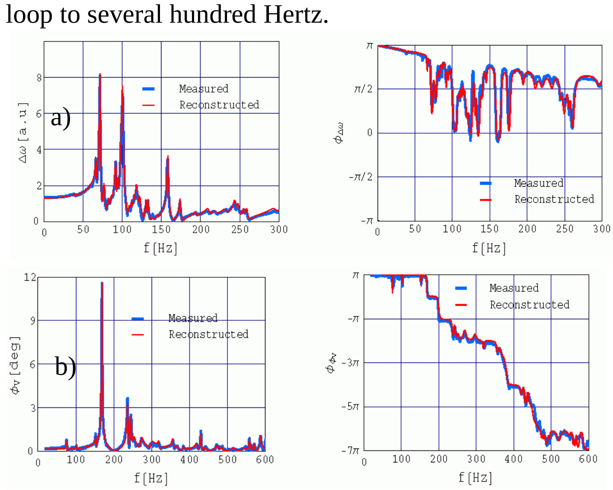

Fig.2: Transfer function from a) Lorentz force to cavity detuning and b) piezo actuator to cavity detuning for SNS cavity (courtesy M. Doolean)

The failure of these attempts can be explained by the mechanical resonances of the cavity which introduce several second order poles in the transferfunction between

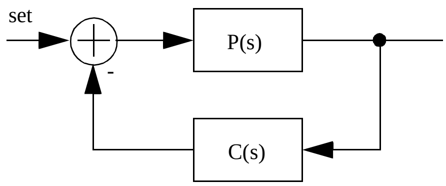

Fig.3: Feedback configuration with plant P(s) and controller C(s)

piezo actuator input and the cavity resonance frequency measured with a phase detector. In practice the mechanical transfer functions of multicell cavities such as employed at the TESLA Test facility or at SNS are quite complicated because of the large number of resonances up to several kHz. In summary the issues related to the control of microphonics are:

- mechanical resonances in the transfer function of piezo tuner + delay from propagation of acoustic waves
- vibrations from the environment (microphonics) and piezo tuner couple differently to mechanical resonances
- different mechanical modes couple differently to the resonance frequency of the cavity. No linear superposition of detuning from individual mechanical modes possible i.e system is nonlinear.
- mechanical modes excited with large amplitude can potentially modulate the energy gain in multicell cavities significantly.

CONTROL OF MICROPHONICS

The goal is to find an acceptable controller C(s) for a given transferfunction P(s) of the piezo actuator in the control configuration shown in Figure 2.
The controller must fulfill several requirements

- Feedback loop must be stable i.e. the open loop transferfunction D(s)=P(s)C(s) must change the phase less than 180 deg. up to unity gain frequency.
- For fast reponse the phase margin should be at least 30-60 deg.
- Good error suppression i.e. high gain of D(s) at frequencies which need to be controlled (up to several hundred Hz). The gain of D(s) should roll-off fast at higher frequencies to guarantee stability.
- Robust against small changes of the transfer function of the piezo actuator.

After choosing the desired open-loop frequency response D(s) the controller can be designed as

$$C(s) = \frac{D(s)}{P(s)}$$

A typical desired open loop transfer function would be a gain of 100 (= 40 dB) for frequencies from DC up to a few hundred Hz, then a steep roll-off (for example 3rd order low-pass with 60 dB/dec), a reduction of roll-off to 20 dB when unity gain is reached (this can be implemented with 2nd order high pass) followed by a fast roll-off above (2nd order low-pass) at a few kHz to prevent higher frequency resonances to cause instabilities.
With D(s) of 8-th order as described and assuming 10 mechanical resonances up to several kHz, the controller requires fairly high order polynomials (28-th order in the example) to be implemented. With the recent progress in digital signal processing hardware (DSPs and FPGAs) it is nowadays possible to implement such high order controllers with low latencies. For example a 20-th order transferfunction processed by a C67 DSP results in a latency of only 20 microseconds. Implementation on a VIRTEX II FPGA is expected to reduce latencies to below 1 microsecond and that very high order transferfunctions can be realized.

CONTROL OF LORENTZ FORCE DETUNING

The static detuning of a resonator due to the action of Lorentz forces is proportional to the square of the accelerating field. However, in the linac of the TESLA Test Facility, the 9-cell cavities are operated in pulsed mode. In this case the mechanical properties of the cavities must be considered when modeling the time-varying detuning of the cavity.

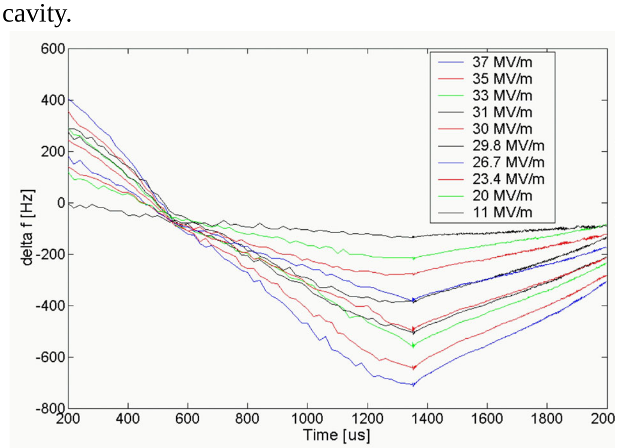

Fig.4: Lorentz force detuning in TESLA cavity AC73

The measured time dependence (Fig. 4) of the Lorentz force detuning is almost linear during the flat-top i.e. during the beam pulse and changes by approximately +-200 Hz at 25 MV/m. It is important to note that the time-varying cavity detuning is reproduced very accurately from pulse to pulse and is only slightly (up to +-10 Hz) modulated by microphonics. The additional power needed for control shows a quadratic dependence of the cavity detuning with the accelerating field and becomes excessive at high gradients. While the power requirements at 25 MV/m are moderate (up to 25% of additional rf power), the requirements at 35 MV/m (up to 100%) are intolerable and necessitate a scheme for compensation of the Lorentz force detuning by use of a fast mechanical tuner. The improvement in field stability by such a compensation scheme is shown in Figure 5 for a TESLA cavity operated at 35 MV/m.

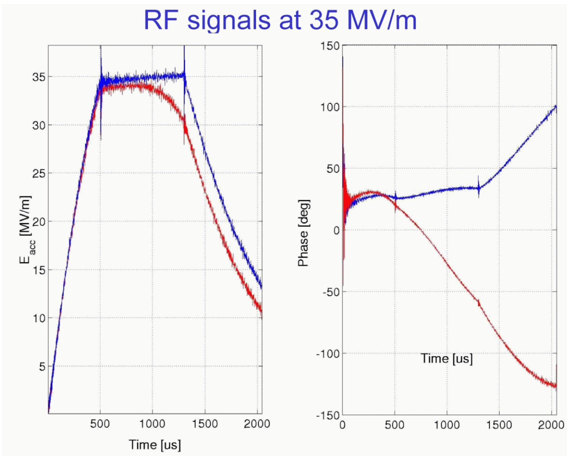

Fig.5: Cavity field during compensation of Lorentz force detuning

The corresponding detuning is shown in Figure 5. The feedforward signal made use of resonant enhancement of the piezo tuning range by excitation of a mechanical resonance of the cavity at 230 Hz. Thereby is has been possible to compensate about 1 kHz of cavity detuning while the static frequency change of the piezotuner has been only 200 Hz. The resonant compensation worked amazingly well since the resonance frequency of 230 Hz allows for linear compensation for the rf pulse duration of 1.3 ms. Stable compensation could be achieved during many hours of operation without re-adjustment of the feedforward table.

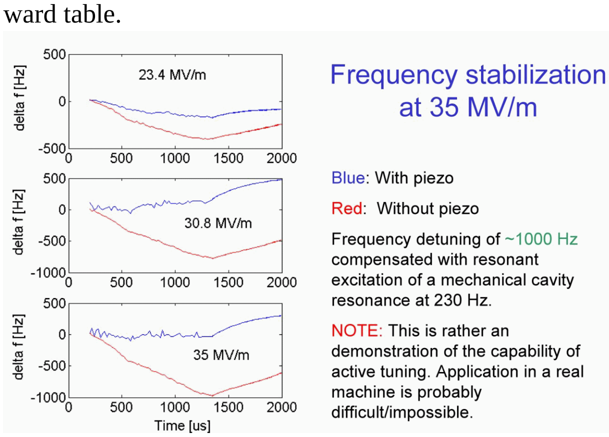

Fig.6: Compensation of Lorentz force detuning

ACTUATORS FOR CONTROL

The basic choices of actuators for fast mechanical frequency tuners are piezoelectric and magnetostrictive elements. Due to the widespread availability of piezoelectric actuators they appear the natural choice for a fast mechanical tuner. Recent developments have led to increased lifetime. Typical examples for piezo actuators are shown in Figure 6.

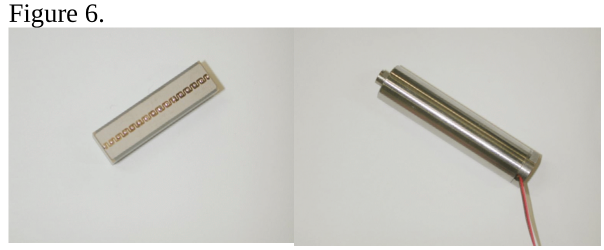

Fig.7: Examples for piezo actuators. a) low voltage piezo stack with ceramic coating and b) packaged version of with integrated mechanical preloading.

The lifetime of a piezo actuator depends strongly on the mechanical pre-load which should be of the order of 1 kN/cm^2. The integration of a piezo actuator with the existing motorized frequency tuner for the TESLA cavities is shown in Figure 8. The piezo fixture which holds 2 piezo allows for a actuator/sensor configuration where the 2nd piezo acts as a sensor for vibrations and can be used as a spare actuator.

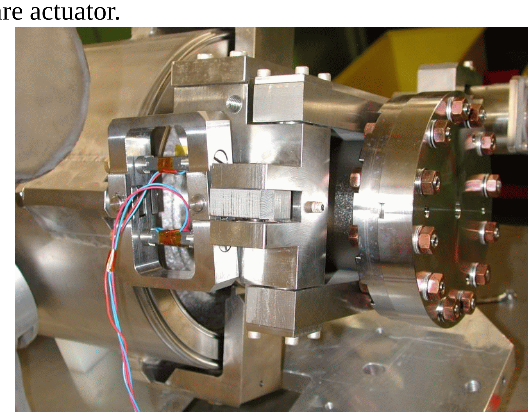

Fig.8: Installation of piezotuner in cryostat

A typical failure mode of piezo actuator is the shortening of electrodes due to cracks in the ceramic which developed during pulsed operation. A possible diagnostic for the detection of developing cracks in the material could be electrical impedance measurement as shown in Figure 9. Since the electrical resonances reflect the mechanical resonances which in turn represent the mechanical properties of the piezo stack, it might be possible to detect partial damage of the piezo. The resonance frequencies depend on the mechanical pre-load and could be used to measure the mechanical forces acting on the piezo actuator. Another choice for fast mechanical tuner are magnetostrictive elements which could allow for larger stroke, tolerance of larger pre-loads and avoid the problem of shortened electrodes or damage by excessive operating voltages due to the operating in a magnetic field generated by a superconducting solenoid. Disadvantaged could the large operating currents and associated magnetic stray fields. In the near future a significant development of magnetostrictive elements for fast frequency tuning is expected.

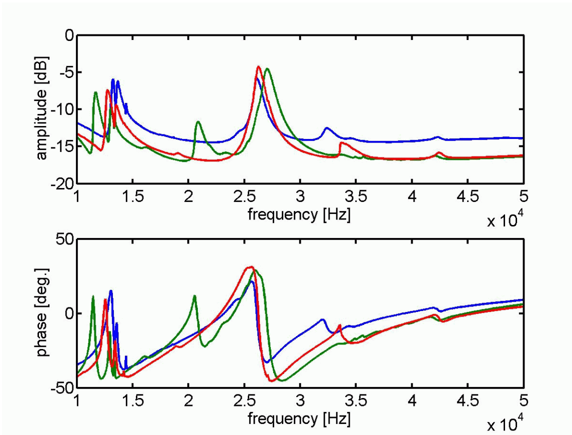

Fig.9: Impedance of 3 piezo actuators of the same model

DIGITAL SIGNAL PROCESSING

Digital signal processing is essential for the success of development of fast tuning algorithms for control of Lorentz force detuning and microphonics. In the latter case feedback with quite complicated transfer functions will be required which can be only realized in high speed digital signal processing electronics. With DSP based systems as shown in Figure 10 latencies of the order of 20 microseconds can be achieved for 20x20 matrix multiplications while FPGA based system are about 10 times faster.

Fig.10: Digital signal processor board with 8 Gigalink interfaces for fast analog and digital IO.

CONCLUSION

The need for fast mechanical tuners for control of Lorentz force detuning and microphonics has triggered a development of tuners based on piezo and magnetostrictive tuner. Lifetime of the tuner is crucial to performance and depends strongly on the mechanical preload which is difficult to predict at cryogenics temperatures. Therefore the development of in situ force measurements is essential. Transferfunctions from piezotuner to cavity detuning and Lorenz force to cavity detuning have been measured and show a complex resonances for multi-cell cavities. Therefore application of feedback for control of microphonics will be a challenging task. Lorentz force compensation can be accomplished with feedforward and is possible if the piezotuner couples to the same resonances as the Lorenz force.

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